

NsG-395

Scientific Report No. 2

A CLASSIFICATION OF THE DISPERSION SURFACES  
IN A MAGNETO-IONIC MEDIUM AND A STUDY  
OF THE ASSOCIATED RADIATION PATTERNS

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OTS PRICE

and

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BOOK \$ 2.00  
CALLEROFF \$ .50

October 1964

N65-10837

(ACCESSION NUMBER)	(THRU)	(CODE)	(CATEGORY)
37	1	35	
(PAGES)			
6859502			
(NASA CR OR TMX OR AD NUMBER)			

FACILITY FORM 602

Sponsored by the National Aeronautics  
and Space Administration under Grant NsG-395

UNPUBLISHED PRELIMINARY DATA

Department of Electrical Engineering  
Engineering Experiment Station  
University of Illinois  
Urbana, Illinois

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#### ACKNOWLEDGEMENT

The research reported in this study was sponsored by the National Aeronautics and Space Administration under Contract NASA NSG 395.

The authors wish to acknowledge the work of Mr. S. Laxpati, who wrote the computer program, and the work of Mr. S. Kuo, who drafted the far field patterns presented herein.

ABSTRACT

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This study commences by demonstrating the important role played by the dispersion surfaces in the determination of the far fields of an infinitesimal dipole in a lossless, cold magneto-ionic medium. The dispersion surfaces are then classified, according to their shapes, for different ranges of the plasma parameters. A comprehensive group of radiation patterns is then given including far fields for each of the fourteen classified ranges of the plasma parameters.

*author*

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## 1. INTRODUCTION

In recent years considerable attention has been directed towards the study of radiation from sources in anisotropic media of an infinite homogeneous nature. It is of great interest to study the case of a cold lossless medium for different combinations of electron density and applied steady magnetic field. The Appleton-Hartree equation constitutes the mathematical description of the "plasma" that is often used in this analysis. This problem has been studied extensively. [Bunkin, 1957, Kuehl, 1960, and Arbel and Felsen, 1963]. Of more specific interest are the far fields of an infinitesimal dipole. Analytic expressions for the asymptotic fields have been available for some time in the literature but no extensive numerical calculations have been made for the far field patterns of a short dipole. The purpose of this study is to briefly summarize Kuehl's method of calculation, to demonstrate the important role the dispersion surfaces play in the calculation of the far fields and to classify these various types of dispersion surfaces according to specific ranges of the plasma parameters. Explicitly, these parameters are the electron density, applied steady magnetic field and frequency, which may be conveniently represented in terms of the dimensionless parameters  $X$  and  $Y$ , to be defined later. The study embraces infinite, anisotropic, homogeneous media and treats only the lossless case of a cold plasma. The paper includes a brief description of numerical calculation techniques and the study concludes with the presentation of the far field patterns of an infinitesimal dipole calculated for several different combinations of the plasma parameters.

## 2. THEORETICAL CONSIDERATIONS

Maxwell's Equations in an anisotropic homogeneous medium with a relative permittivity dyadic  $\bar{\bar{K}}$  and free space permeability  $\mu_0$  are:

$$\nabla \times \bar{H} = j \omega \epsilon_0 \bar{\bar{K}} \bar{E} + \bar{J} \quad (1)$$

$$\nabla \times \bar{E} = - j \omega \mu_0 \bar{H} \quad (2)$$

where  $\bar{E}$  and  $\bar{H}$  are electric and magnetic field vectors,  $\bar{J}$  is the current density, and  $\omega$  is the angular frequency. A harmonic time dependence of  $e^{j\omega t}$  is assumed.

In a plasma with a  $\hat{z}$ -directed steady magnetic field, the relative permittivity dyadic  $\bar{\bar{K}}$  is of the form

$$\bar{\bar{K}} = \hat{x} \hat{x} K' + j \hat{x} \hat{y} K'' - j \hat{y} \hat{x} K'' + \hat{y} \hat{y} K'' + \hat{z} \hat{z} K_0 \quad (3)$$

where

$$K_0 = 1 - \frac{X}{U}, \quad K' = 1 - \frac{XU}{U^2 - Y^2}, \quad K'' = - \frac{XY}{Y^2 - U^2}$$

$$X = \frac{\omega_N^2}{\omega^2}$$

$$Y = \frac{\omega_H}{\omega}, \quad \omega_N^2 = \frac{Ne^2}{m\epsilon_0}, \quad \omega_H = \frac{eB_0}{m}, \text{ a positive number}$$

$$U = 1 - jZ = 1 - j \frac{\nu}{\omega}, \quad \nu = \text{collision frequency}$$

$$N = \text{electron density}$$

$$B_0 = \text{DC magnetic flux density}$$

$$e = \text{magnitude of electron charge}$$

$$m = \text{electron mass}$$

$$k_0 = 2\pi/\lambda_0 = \text{free space wave number}$$

$$\lambda_0 = \text{free space wavelength}$$

Taking curl of Equation (2) and using (1), obtain

$$\nabla \times \nabla \times \bar{E} - \omega^2 \mu_0 \epsilon_0 \bar{K} \bar{E} = -j \omega \mu_0 \bar{J}. \quad (4)$$

A general solution of (4) may be expressed as

$$\bar{E}(\bar{r}) = \int_V \bar{\Gamma}(\bar{r}, \bar{r}') \cdot \bar{J}(\bar{r}') dv' \quad (5)$$

where  $\bar{\Gamma}(\bar{r}, \bar{r}')$  is the dyadic Green's function, the integration being performed over the volume  $V$  containing the source currents. For an infinitesimal dipole,

$$\bar{J}(\bar{r}) = \int_V \bar{U} \bar{J}(\bar{r}') \delta(\bar{r}) dv' \quad (6)$$

where  $\bar{U}$  is the unit dyadic, and  $\delta(\bar{r})$  is the three-dimensional Dirac delta function. Substituting (5) and (6) into (4) and using some well-known vector identities we obtain the following equation satisfied by the dyadic Green's function:

$$(-\nabla^2 \bar{U} + \nabla \nabla - \omega^2 \mu_0 \epsilon_0 \bar{K}) \bar{\Gamma}(\bar{r}) = -j \omega \mu_0 \bar{U} \delta(\bar{r}). \quad (7)$$

Now define the three-dimensional Fourier transform pair:

$$\tilde{\bar{f}}(\bar{K}) = \int_{-\infty}^{\infty} \bar{f}(\bar{r}) e^{j \bar{K} \cdot \bar{r}} d\bar{r}, \quad \bar{f}(\bar{r}) = \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} \tilde{\bar{f}}(\bar{K}) e^{-j \bar{K} \cdot \bar{r}} d\bar{K}.$$

Transforming Equation (7) and letting

$$\bar{M}(\bar{K}) = \bar{K} \cdot \bar{K} \bar{U} - \bar{K} \bar{K} - \omega^2 \mu_0 \epsilon_0 \bar{K} \quad (8)$$

one obtains

$$\bar{M}(\bar{K}) \bar{\Gamma}(\bar{K}) = -j \omega \mu_0 \bar{U}.$$

Premultiplying by  $\bar{\bar{M}}^{-1}$  and taking the inverse Fourier transform one obtains:

$$\bar{\bar{\Gamma}}(\bar{r}) = - \frac{j \omega \mu_o}{8\pi^3} \int_{-\infty}^{\infty} \bar{\bar{M}}^{-1} e^{-j\bar{K} \cdot \bar{r}} d\bar{K} \quad (9)$$

where  $\bar{M}^{-1} = \frac{\bar{\bar{P}}}{|\bar{\bar{M}}|}$ .

Removing  $\bar{\bar{P}}$  outside the integral in its operator form,  $\bar{\bar{D}}$ , we have

$$\bar{\bar{\Gamma}}(\bar{r}) = \frac{j \omega \mu_o}{8\pi^3} \bar{\bar{D}} \int_{-\infty}^{\infty} \frac{1}{|\bar{\bar{M}}|} e^{-j\bar{K} \cdot \bar{r}} d\bar{K} \quad (10)$$

$$\text{Now } |\bar{\bar{M}}| = -\omega^2 \mu_o \epsilon_o K_o (K_z^2 - s_z^2) (K_z^2 - t_z^2) \quad (11)$$

where  $s_z$  and  $t_z$  are the roots of  $|\bar{\bar{M}}| = 0$  [Allis et al., 1963]. Next consider the asymptotic evaluation of the integral appearing in (10). Let

$$I(\bar{r}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{e^{-j\bar{K} \cdot \bar{r}}}{(K_z^2 - s_z^2) (K_z^2 - t_z^2)} dK_x dK_y dK_z \quad (12)$$

Integrate the above equation over  $K_z$  using the calculus of residues and transform the  $x, y, z$  system to a  $r, \theta, \phi$  spherical coordinate system. Also the transform variables  $K_x$  and  $K_y$  can be transformed into a polar coordinate system  $\rho, \beta$ . After integrating over  $\beta$  the remaining integral can be evaluated using the saddle point method for large  $k_o r$ , the result being that asymptotically

$$I(\bar{r}) = \frac{1}{k_o r} \sum_{m=1}^2 \sum_n (-1)^m A_{mn}(\theta) e^{-j \chi_{mn}(\theta) k_o r} \quad (13)$$

where

$$A_{mn}(\theta) = - \left( \frac{2\pi^2 j \cos \theta}{k_o^3 \sqrt{\sin \theta} \cos(\psi_{mn} - \theta) \cos \psi_{mn}} \right) \times$$

$$\chi_{mn} = \sqrt{\frac{n_m \sin \psi_{mn}}{[(K' - K_0)^2 n_{mn}^4 \sin^4 \psi_{mn} - 4K_0^2 K''^2 (n_{mn}^2 \sin^2 \psi_{mn} - K_0^2)] [(n_{mn}'' - n_{mn}') \cos(\psi_{mn} - \theta) - 2n_{mn}' \sin(\psi_{mn} - \theta)]}} \quad (14a)$$

and

$$\chi_{mn}(\theta) = n_{mn}(\psi_{mn}) \cos(\psi_{mn} - \theta). \quad (14b)$$

Note that if  $n_m$  is imaginary,  $e^{-j\chi_{mn} k_0 r}$  decays exponentially and there will be no far field.  $n_{mn}'$  and  $n_{mn}''$  denote the first and second derivative of  $n_m$  respectively, evaluated at  $\psi_{mn}$ . Here

$$n_m^2(\psi) = \frac{[K'(K' - K_0) - K''^2] \sin^2 \psi + 2K'K_0 \pm \sqrt{[K'(K' - K_0) - K''^2]^2 \sin^4 \psi + 4K_0^2 K''^2 \cos^2 \psi}}{2(K' \sin^2 \psi + K_0 \cos^2 \psi)} \quad (15)$$

$n_m(\psi)$ ,  $m = 1, 2$  (ordinary, extraordinary), are the two dispersion curves and the saddle point condition is

$$\frac{d}{d\psi} [n_m(\psi_m) \cos(\psi_m - \theta)] = 0, \quad m = 1, \text{ and } 2. \quad \text{i.e.} \quad \frac{d}{d\psi} (n_m) = n_m \tan(\psi - \theta). \quad (16)$$

It may be shown that in general there is more than one solution of (16) and these solutions can be identified by  $\psi_{mn}$  where  $n$  may be 1, 2, or 3, depending on the shape of the  $n_m$  curves. The details of this evaluation are to be found in Kuehl. The dyadic operator  $\bar{\bar{D}}$  must now be evaluated in the coordinate system  $(\Gamma, \theta, \varphi)$ , to finally yield  $\bar{\bar{\Gamma}}(\mathbf{r})$ , the Green's dyadic, which can be regarded as a  $3 \times 3$  matrix. To calculate the far fields of a  $\hat{z}$ -directed infinitesimal dipole only three of these 9 components need be calculated. They are:

$$\Gamma_{xz} = G \sum_{m=1}^2 \sum_n \left\{ (-1)^m n_{mn}^2 \sin \psi_{mn} \cos \psi_{mn} [(n_{mn}^2 - K') \cos \varphi - jK'' \sin \varphi] F_{mn} \right\} \quad (17)$$

$$\Gamma_{yz} = G \sum_{m=1}^2 \sum_n \left\{ (-1)^m n_{mn}^2 \sin \psi_{mn} \cos \psi_{mn} [(n_{mn}^2 - K') \sin \varphi + jK'' \cos \varphi] F_{mn} \right\} \quad (18)$$

$$\Gamma_{zz} = G \sum_{m=1}^2 \sum_n \left\{ (-1)^m [(n_{mn}^2 - K') (n_{mn}^2 \cos^2 \psi_{mn} - K'^2) - K''^2] F_{mn} \right\} \quad (19)$$

where

$$G = \frac{j\omega \mu_0 k_o^3}{8\pi^3 r} \quad \text{and} \quad F_{mn} = A_{mn}(\theta) e^{-j\chi_{mn}(\theta) k_o r}. \quad (20)$$

The infinitesimally small dipole of dipole moment  $\bar{p}$  located at the origin yields an electric field given by

$$\bar{E}(\bar{r}) = j\omega \bar{\bar{\Gamma}}(\bar{r}) \bar{p}. \quad (21)$$

This equation may be employed to calculate the far field patterns after inserting the asymptotic form of  $\bar{\bar{\Gamma}}(\bar{r})$  in (21).

### 3. REFRACTIVE INDEX SURFACES

As was demonstrated in the previous section the refractive index surfaces,  $n_m(\psi)$ ,  $m = 1, 2$ , play an important role in the determination of the far fields of a source in a plasma. It is necessary to have a description of the refractive index surfaces for each mode of propagation. The shape of these surfaces is a function of the dimensionless parameters  $X$  and  $Y$  which are used to describe the lossless ( $Z = 0$ ) medium. These surfaces are surfaces of revolution about an axis parallel to the direction of the imposed steady magnetic field. Thus two-dimensional plots of the curves, which are cross-sections of the surfaces in an axial plane, serve to describe the complex refractive index surfaces. Another form of equation (15) in terms of  $X$  and  $Y$  is:

$$n_m^2(\theta) = 1 - X \left[ 1 - \frac{\frac{1}{2}Y^2 \sin^2 \theta}{1-X} \pm \left\{ \left( \frac{\frac{1}{2}Y^2 \sin^2 \theta}{1-X} \right)^2 + Y^2 \cos^2 \theta \right\}^{\frac{1}{2}} \right]^{-1}. \quad (22)$$

These are the curves which describe the above surfaces for a lossless anisotropic cold plasma. It is common practice to associate the subscript  $m = 1$  with the  $+$  sign and the nomenclature 'ordinary wave', and  $m = 2$  with the  $-$  sign and the 'extraordinary wave'. For the lossless case  $n_m^2(\psi)$  is always real for all values of  $\psi$ . It should also be noted that  $n_m(\psi) = n_m(\pi - \psi)$  and  $n_m(\psi) = n_m(-\psi)$ . Consequently one need only calculate  $n_m(\psi)$  for  $0 \leq \psi \leq \pi/2$ , the rest of the curve being obtained from the above relations. From the last section it is seen that the asymptotic far fields of an infinitesimal dipole are expressible in terms of  $n_m(\psi)$ , and its first and second derivatives evaluated at the saddle points. Deschamps and Kesler [1964] have recently shown that the far fields of a source in a magnetoplasma may be expressed by

$$\bar{F}(r) = \sum_k \frac{-jh}{4\pi r} (\bar{H}_m^\dagger \cdot \bar{\mathcal{M}}) \bar{F}_k(r) \quad (23)$$

where  $h$  is the Gaussian radius of curvature of the refractive index surfaces,  $\bar{\mathcal{M}}$  is a single vector representing electric and magnetic source current densities,

$\vec{H}_m$  is the magnetic eigenvector and  $\vec{F}_k(r)$  is the characteristic (source free) field vector. The important point to note is that the Gaussian radius of curvature of the complex refractive index surfaces is a dominating factor in the determination of the far fields.

It is thus desirable to have a general knowledge of the characteristic shapes of the  $n_m(\psi)$  curves that will be generated by different combinations of electron density and imposed steady magnetic field..

Clemmow and Mulally, [1955], have classified the refractive index curves into eight distinct types, according to certain features of their shapes. These will henceforth be referred to as the characteristic shapes. The regions of the X-Y plane to which these characteristic shapes correspond were given analytically. This classification is extended and clarified somewhat in this study.

The graph of Figure (1) shows the division of the X-Y plane into fourteen separate regions. Each region is numbered according to the kind of characteristic shape of the refractive index surface that exists for those ranges of values of X and Y. The numbers therein refer to the characteristic shapes shown in the lower right hand part of the graph. The numbers are subscripted O or E indicating whether the characteristic shape is associated with the ordinary or extraordinary wave. Only the real parts of the  $n_m(\psi)$  curves are shown. The region where the curves are completely imaginary for all  $\psi$  has not been numbered (i.e.,  $X > 1+Y$ ,  $Y < 1$ ). There are no far fields generated when the medium parameters (X,Y) are in this region.

It should be noted that characteristic shapes numbered 2,4,6 and 8 have points of inflection for some values of  $\psi$ , while the remaining 4 curves have not. Furthermore, curves 1,2,3 and 4 are associated with both ordinary and extraordinary waves while characteristic shapes numbered 5,6,7 and 8 are associated exclusively with extraordinary waves.

Some examples of specific values of (X,Y) will now be given:

- (a)  $X = 100$ ,  $Y = 10$ . This falls within the region marked  $8_E$ . This means that only  $n_2(\psi)$  is real and has the characteristic shape shown by curve 8. Thus only an extraordinary wave exists in the far field. Since  $n_1(\psi)$  is entirely imaginary for all  $\psi$  the ordinary wave does not contribute to the far field.

- (b)  $X = 1.5$ ,  $Y = 10$  lies in the region marked  $4_0$  and  $7_E$ . The ordinary wave is associated with characteristic shape 4 and the extraordinary wave with shape 7.

For a given value of  $m$  there may exist more than one saddle point, that is, more than one solution to Equation (16). There can be either one, two or three saddle points for a given  $m$ . The existence of more than one saddle point occurs for some values of  $\theta$  only for curves containing points of inflection, i.e., those curves numbered 2,4,6 and 8. When these curves are encountered there will be a merging of two saddle points at the point of inflection for some value of  $\theta$  and the single saddle point asymptotic evaluation is no longer valid; one must resort to the double saddle point method of evaluation which involves the Airy integral type of representation, [Arbel and Felsen, 1963].

It is to be noted that the present study extends Clemmow and Mulally's description in that the ordinary and extraordinary waves are associated with the characteristic shapes of the refractive index curves of each of the fourteen regions of the X-Y plane.

#### 4. NUMERICAL CALCULATIONS

The numerical calculation of the far fields of a z-directed dipole, i.e.,  $\bar{J} = \hat{z} \delta(\bar{r})$ , was carried out in four separate stages, for eighteen different sets of (X,Y) as shown on the graph of the X-Y plane embracing all the fourteen regions.

- (a) Computation of refractive index curves was done on the University of Illinois IBM 7094 computer using Equation (22). The curves  $n_1(\psi)$  and  $n_2(\psi)$  were then plotted. The real values of  $n_m(\psi)$  indicate propagation while imaginary values indicate cutoff, as seen in Equation (14-b).
- (b) Computation of the saddle points was accomplished by using a geometrical construction [Mitra and Deschamps, 1962] for the solution of Equation (16) and then iterating to obtain more precise solutions by the Newton-Raphson method. The iterated saddle points were then used as input data to the program for the computation of the far fields.
- (c) The saddle point solutions  $\psi_{mn}$  for a fixed angle  $\theta$  were used in Equations (17) through (21) to compute the electric field which was then transformed into spherical components.
- (d) In certain cases (where  $\psi_{mn} = \theta$ ) at  $\theta=0$  and  $\pi/2$  Equation (14-a) is an indeterminate form. A modified approach for the calculation of  $A_{mn}$  as given by Kuehl is then employed.

Throughout the calculation  $k_o r = 100$  was used. It should be pointed out that in general the total fields may be quite dependent on the magnitude of  $k_o r$  since it affects the phase between the ordinary and extraordinary waves. This is seen in Equation (13). In some cases the individual ordinary and extraordinary components of the electric field behave in a peculiar fashion, but the vector sum yields total fields of a familiar behavior. This is especially true in the case of a near-isotropic plasma (set #4).

## 5. FAR FIELD PATTERNS

At the end of this study the far fields of a  $\hat{z}$ -directed dipole are given for 18 different combinations of the plasma parameters X and Y. These 18 points are shown in Figure 1.

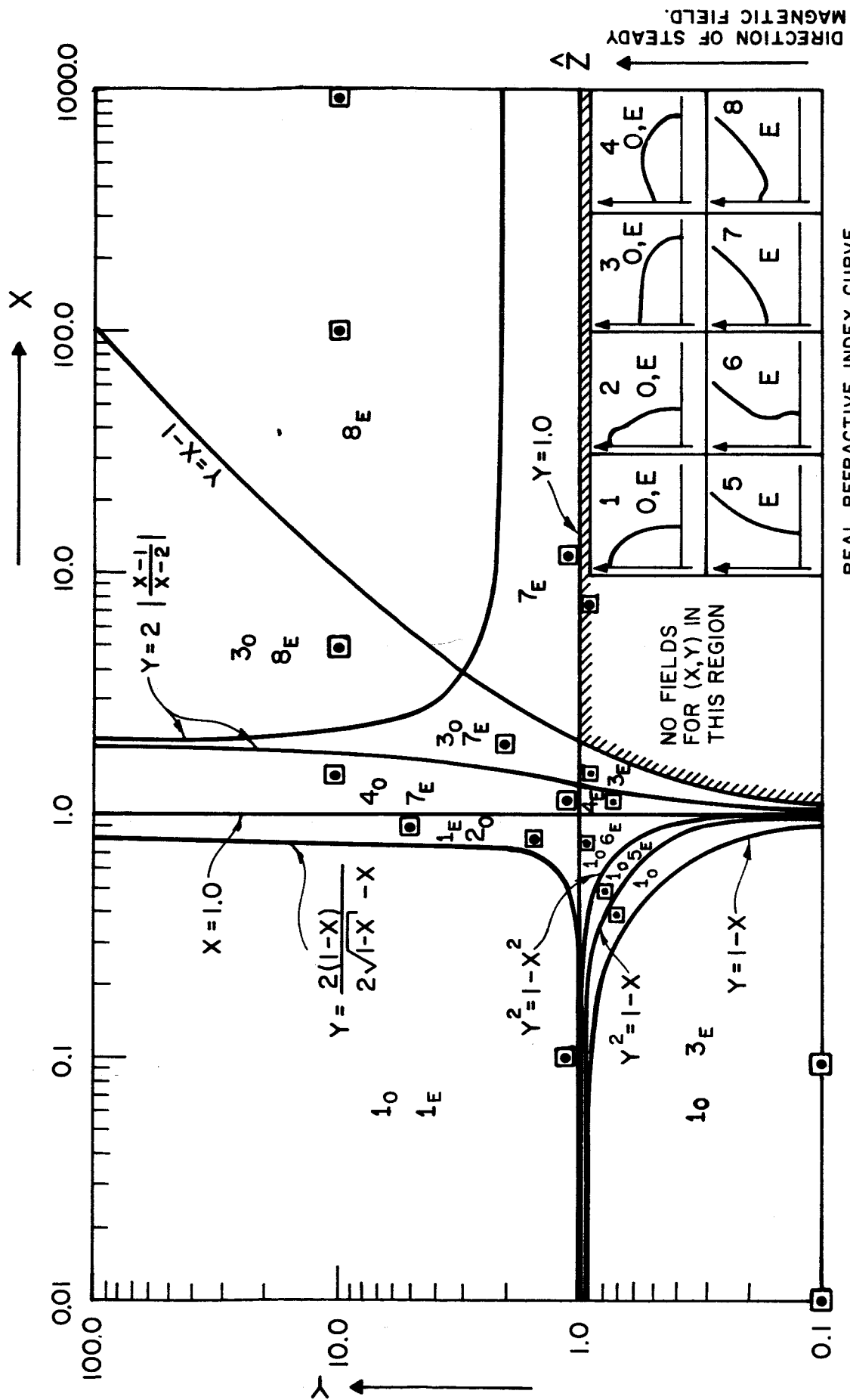
The dispersion surfaces are shown for  $m = 1$  and  $m = 2$ , calculated by Equation (22). Under each dispersion curve are the corresponding ordinary or extraordinary components of the electric field, given in spherical coordinates. They are designated  $E_{R1}$ ,  $E_{\theta 1}$ , and  $E_{\phi 1}$  for the ordinary wave components and similarly for the extraordinary wave components. Broken lines indicate that the computation yields infinities. These infinities occur due to the dispersion curves containing the points of inflection. It should be pointed out that the double saddle point method of evaluation was not used at these points of inflection. The total far fields for  $k_o r = 100$  are shown in the right hand column. All the fields patterns are shown only for  $0 \leq \theta \leq \pi/2$ , the rest of the pattern being found through symmetry properties.

It is interesting to note the behavior of  $E_{\theta T}$  at  $\theta = \pi/2$  in set #8, which is fairly close to the free space condition. This result should be compared with set #4. Although the plasma parameters of set #8 are still near-isotropic, the far-field pattern differs interestingly from the isotropic pattern.

It should be noted that if the dispersion surface is completely imaginary for all  $\psi$ , it is not shown at all because no far fields are generated for that value of  $m$ . The total far fields are those shown for the other value of  $m$  and hence the "total fields" column is left blank to avoid repetition.

## 6. CONCLUSIONS

This study has presented a comprehensive classification of the dispersion curves, and Figure (1) offers a useful graphical representation of this classification. Since the shapes of these curves play an important role in the calculation of the far fields, this classification permits a rough prediction of some of the pattern characteristics of the far fields of a dipole for any choice of the plasma parameters  $X$  and  $Y$ . It can also be useful in the selection of plasma parameters in practical cases where only the ordinary or extraordinary wave is desired. This may find application in the study of pattern synthesis for sources in anisotropic media.



[ ] POINTS IN X-Y PLANE FOR WHICH THE FAR FIELDS OF AN INFINITESIMAL DIPOLE ( $\vec{J} = \vec{J}_0 \delta(\vec{r})$ ) HAVE BEEN CALCULATED.  
 Figure 1. Subdivisions of the X-Y plane; n ( $\psi$ ) - characteristic shapes.

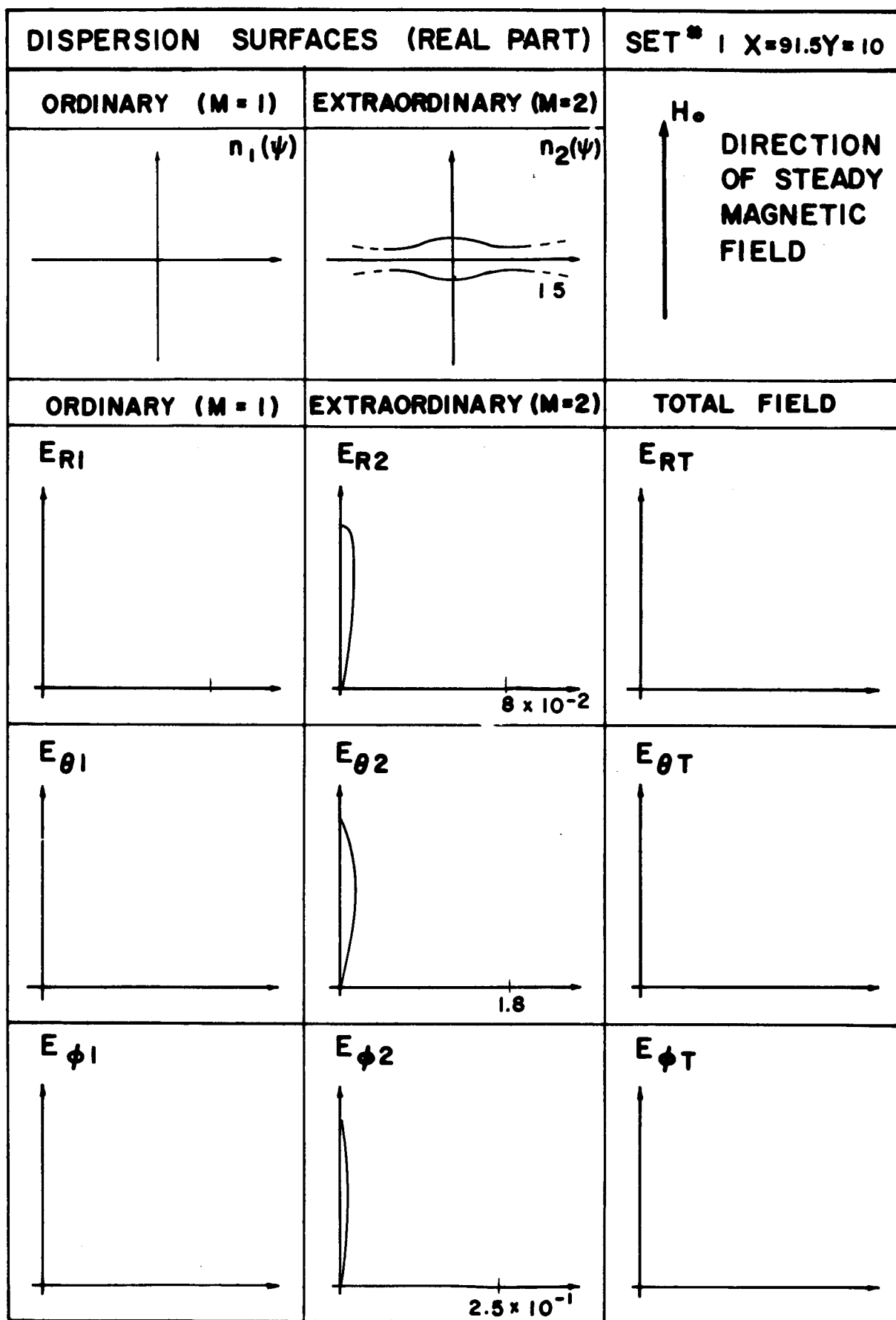


Figure 2.

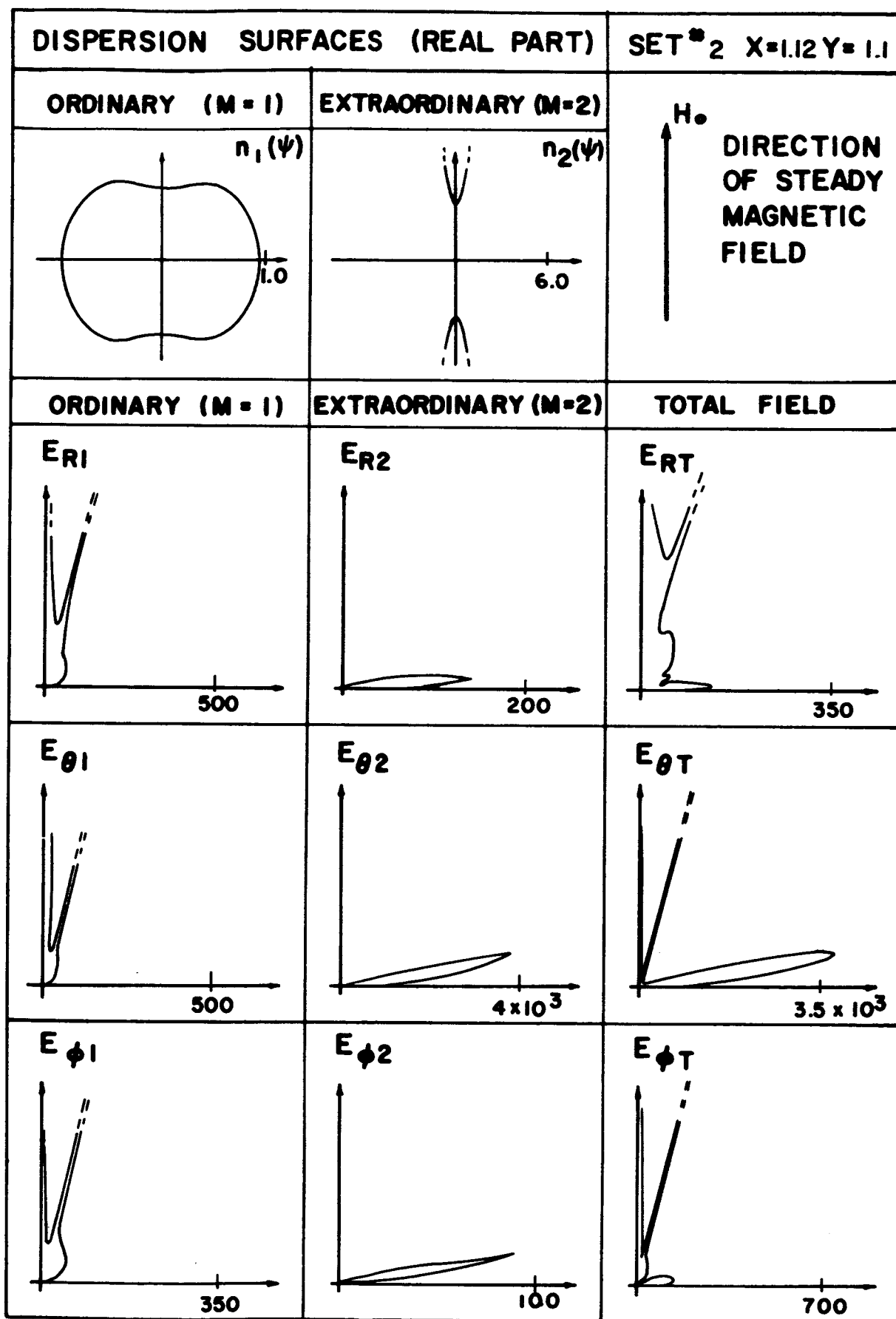


Figure 3.

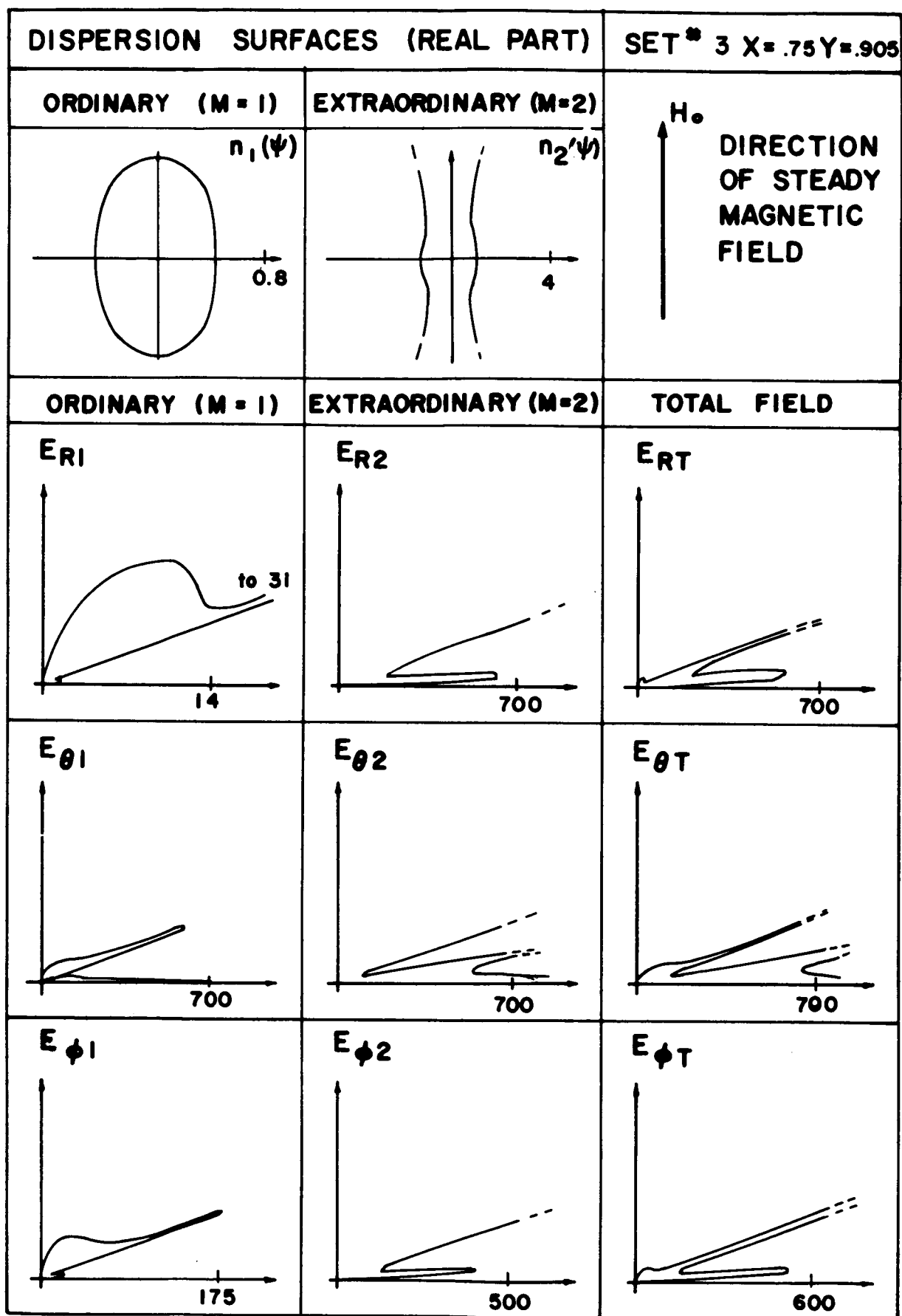


Figure 4.

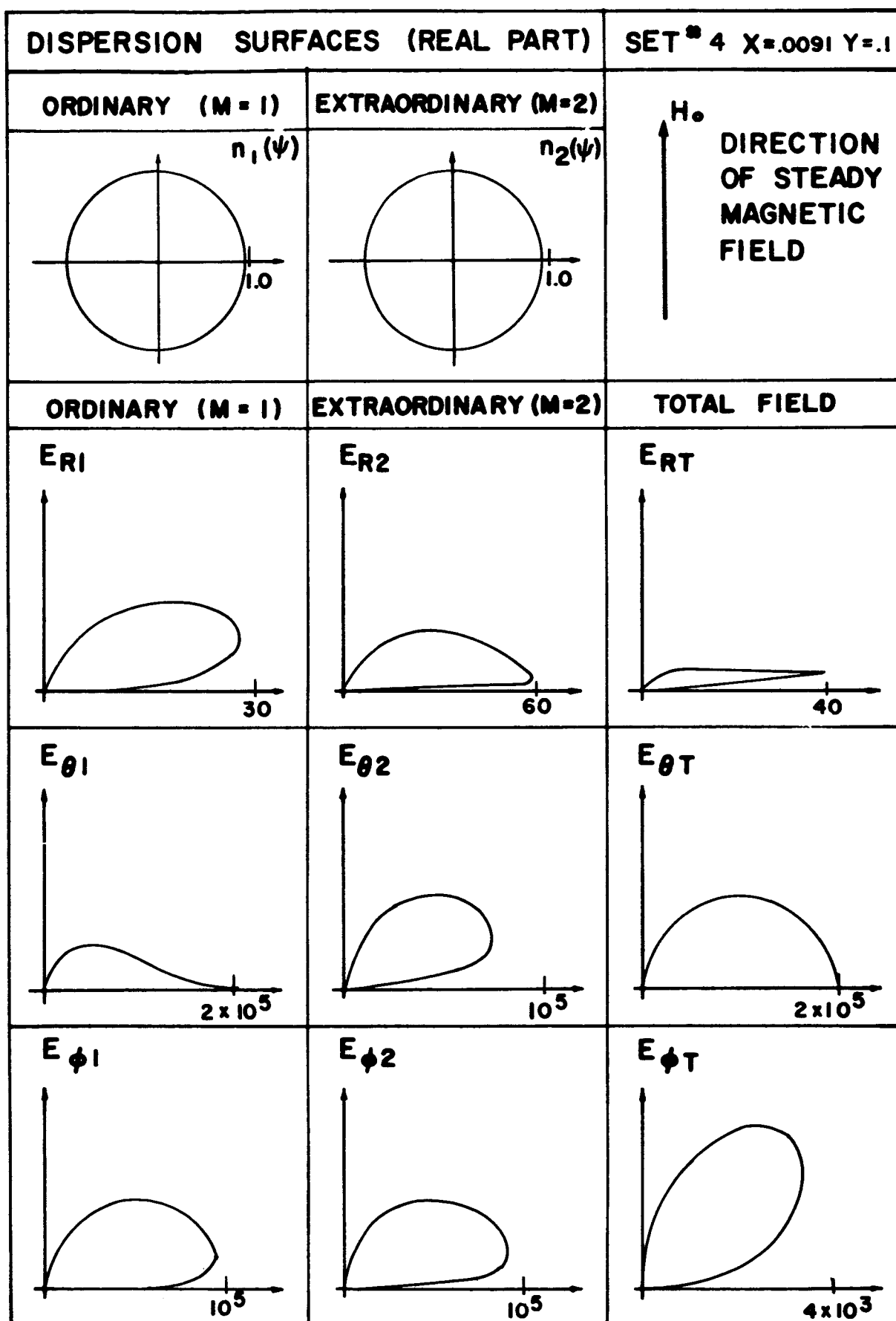


Figure 5.

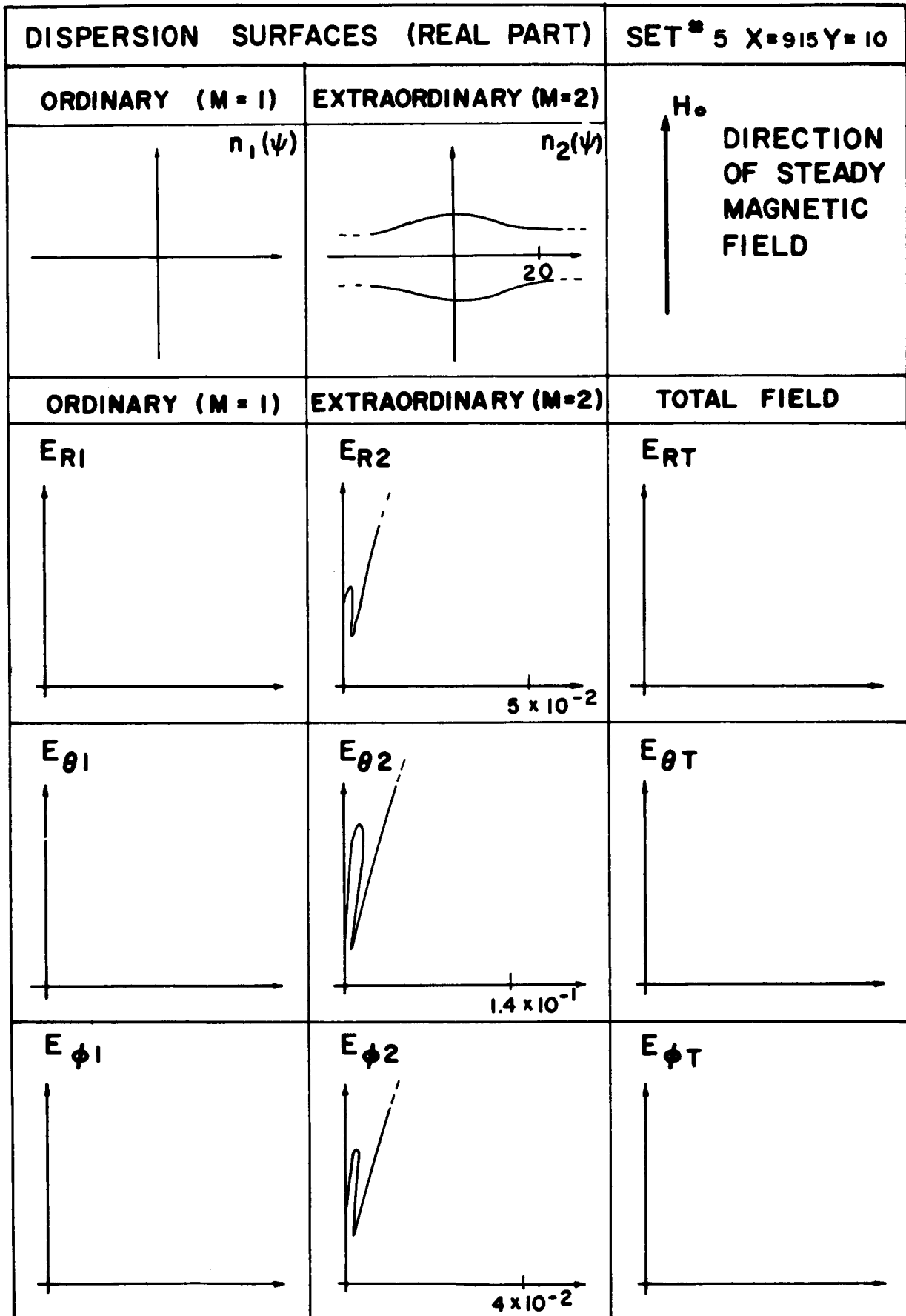


Figure 6.

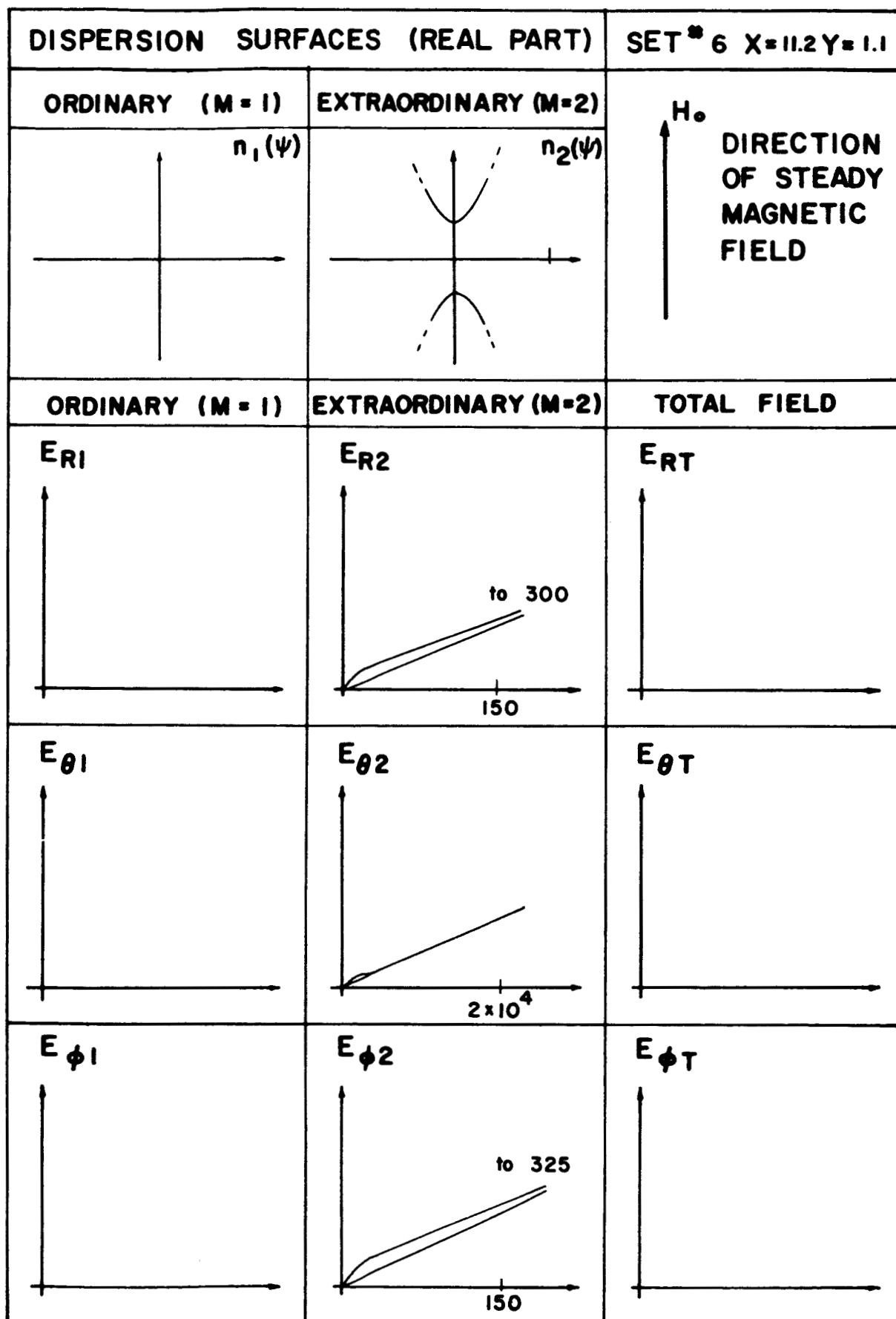


Figure 7.

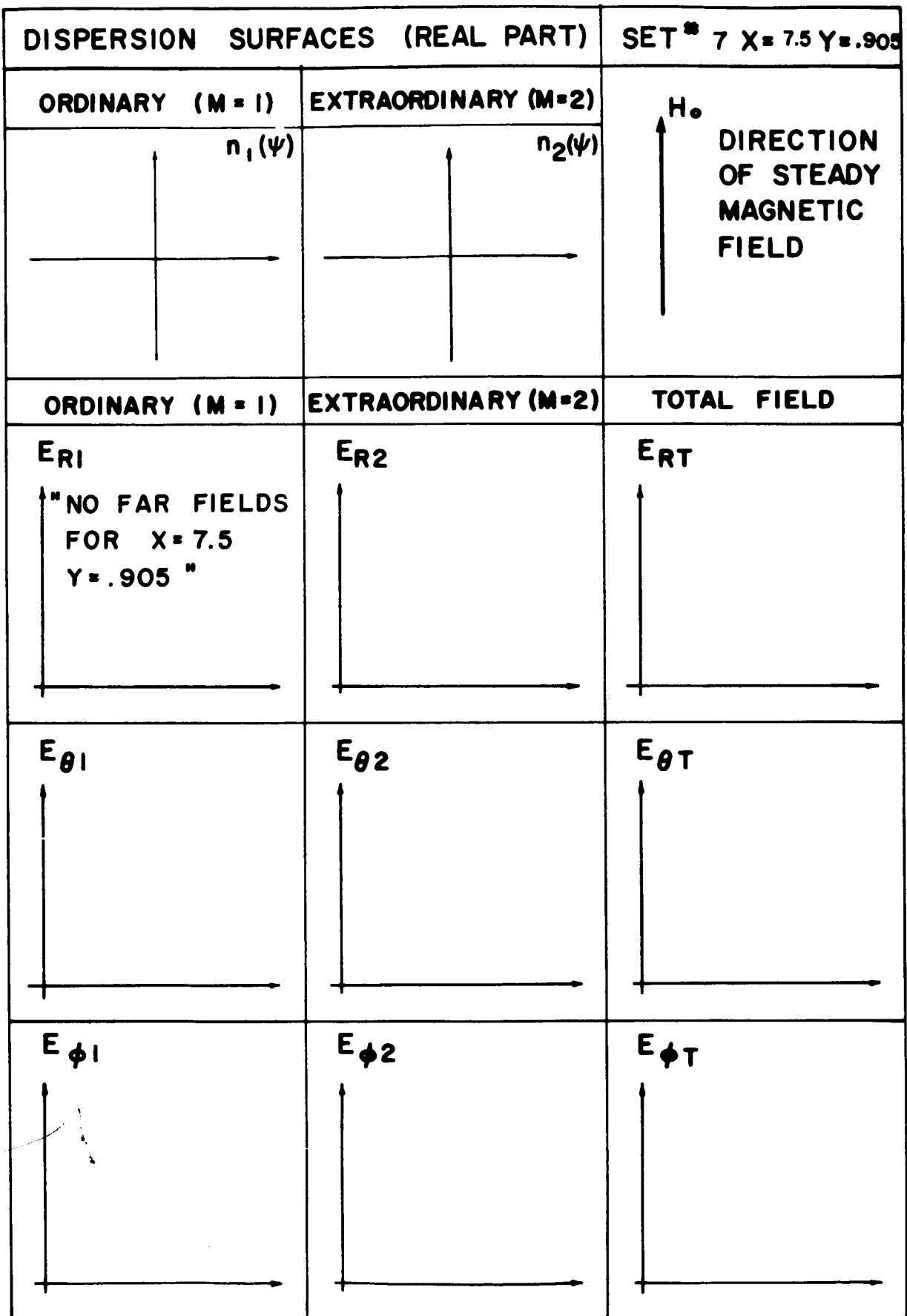


Figure 8.

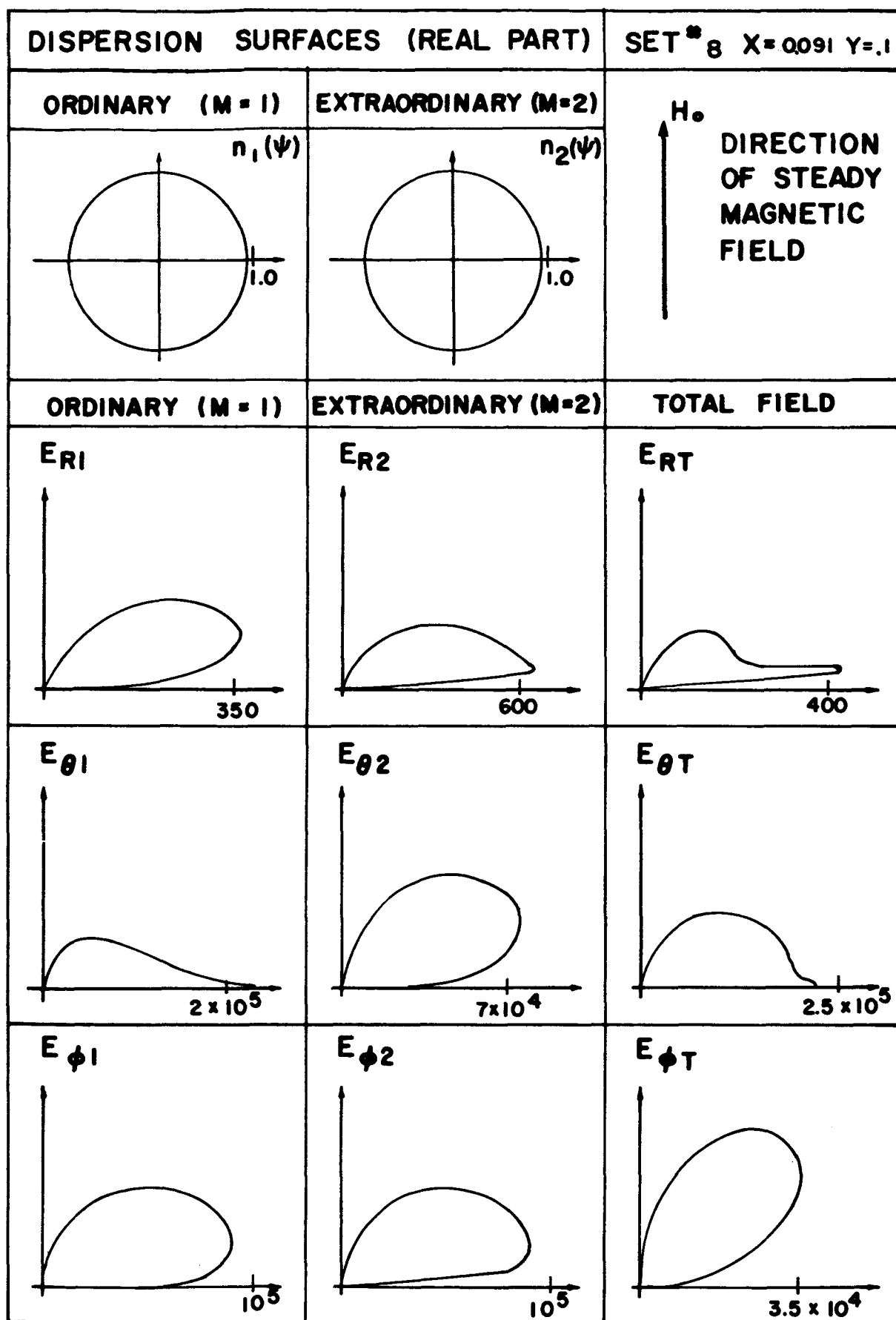


Figure 9.

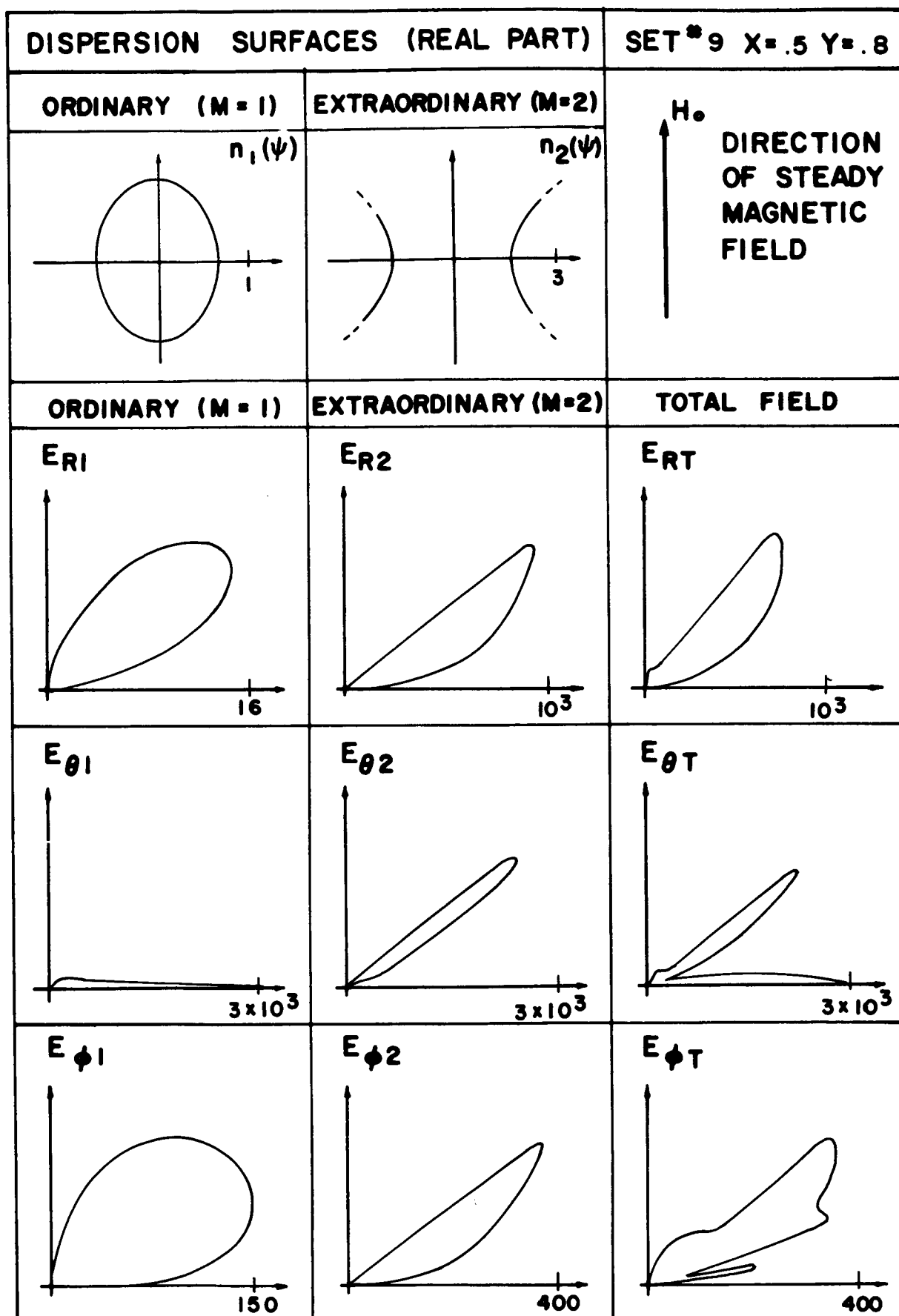


Figure 10.

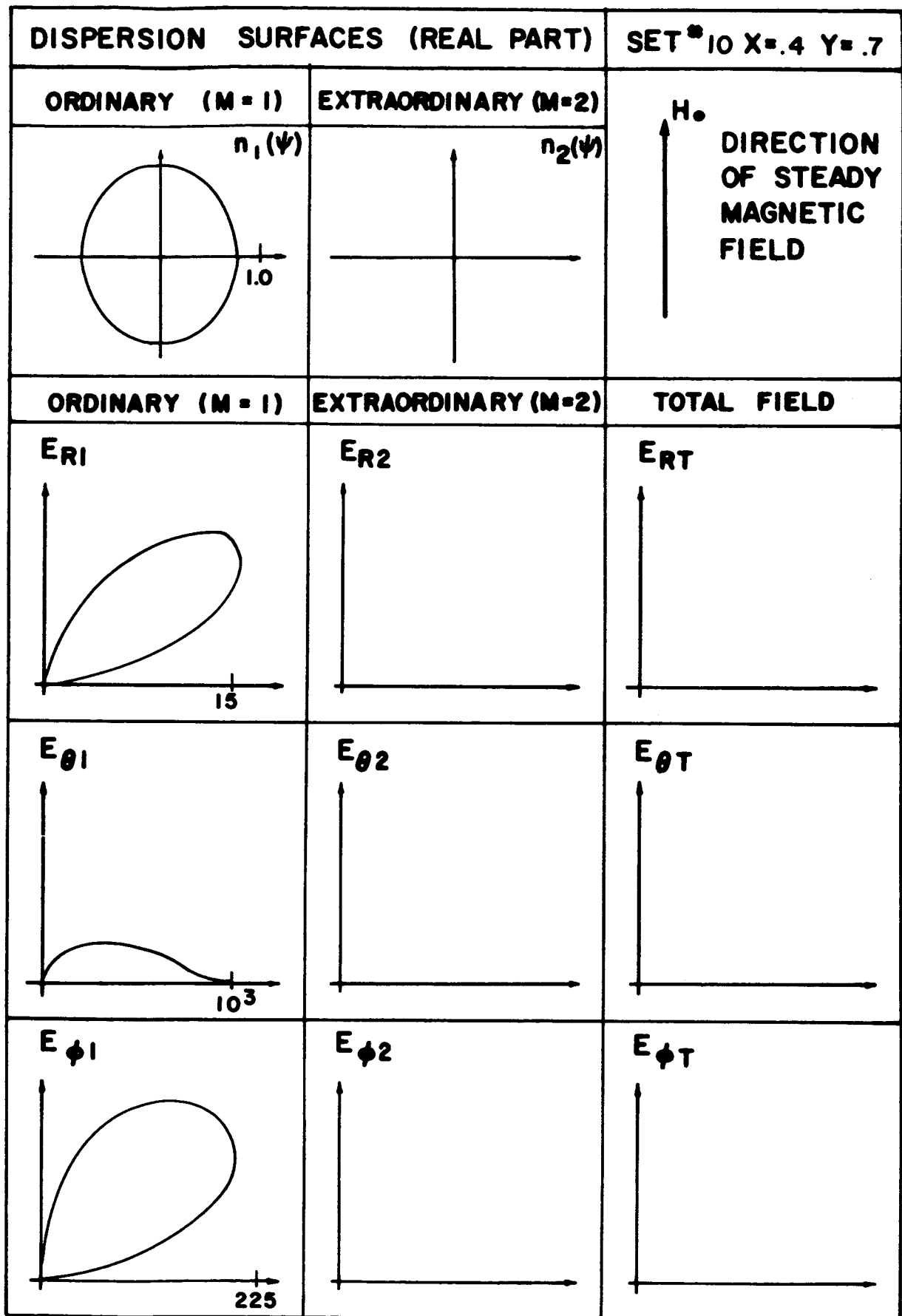


Figure 11.

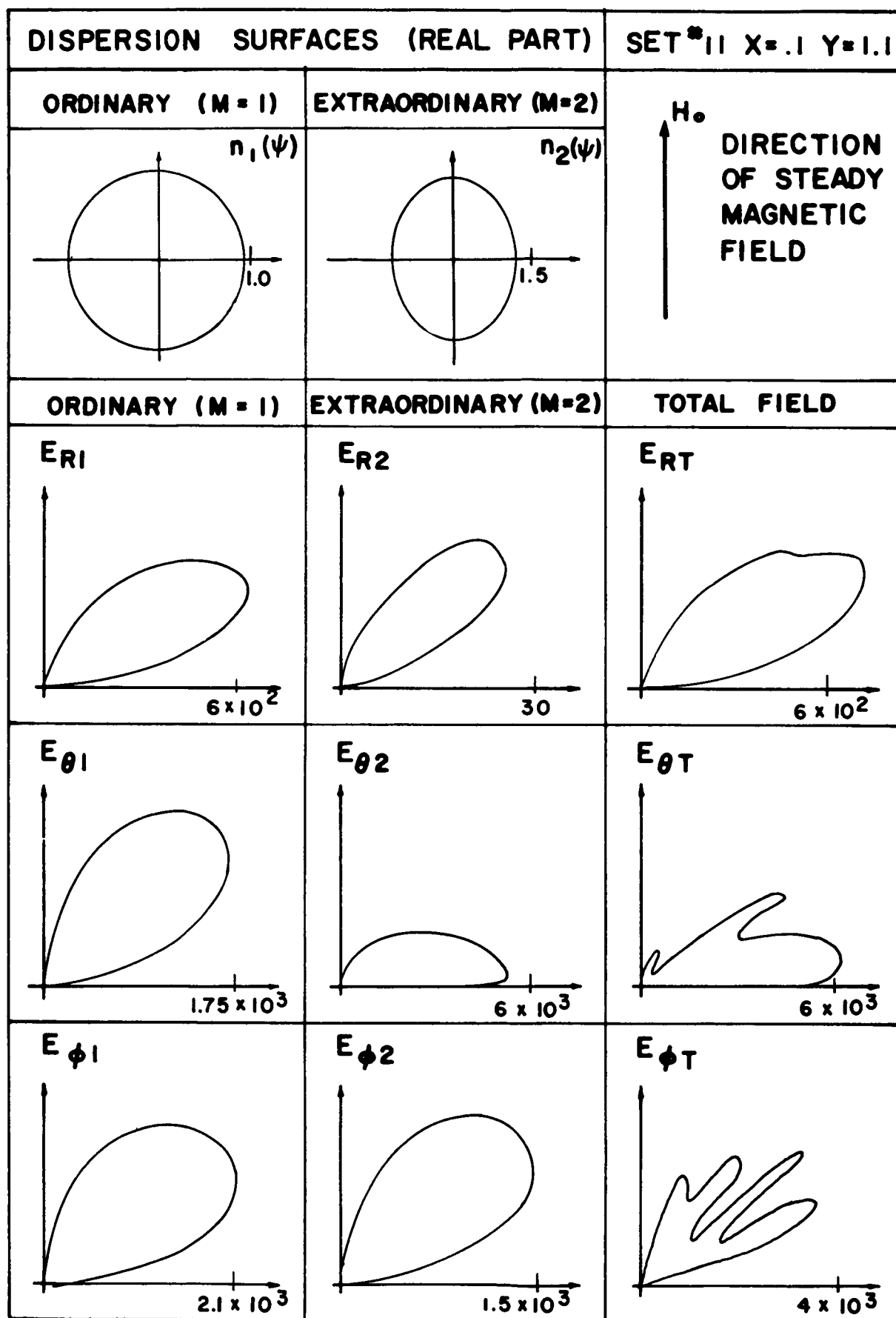


Figure 12.

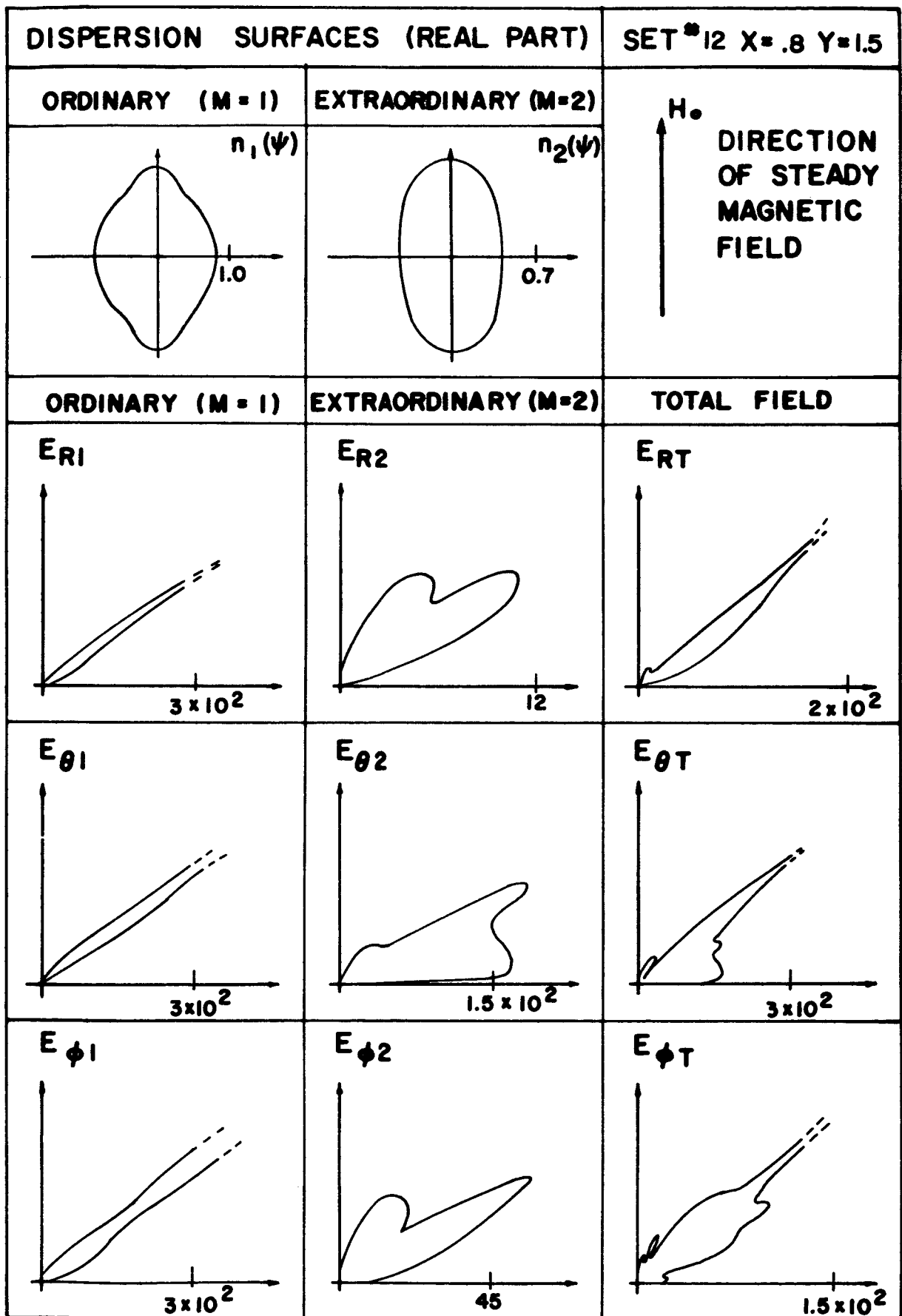


Figure 13.

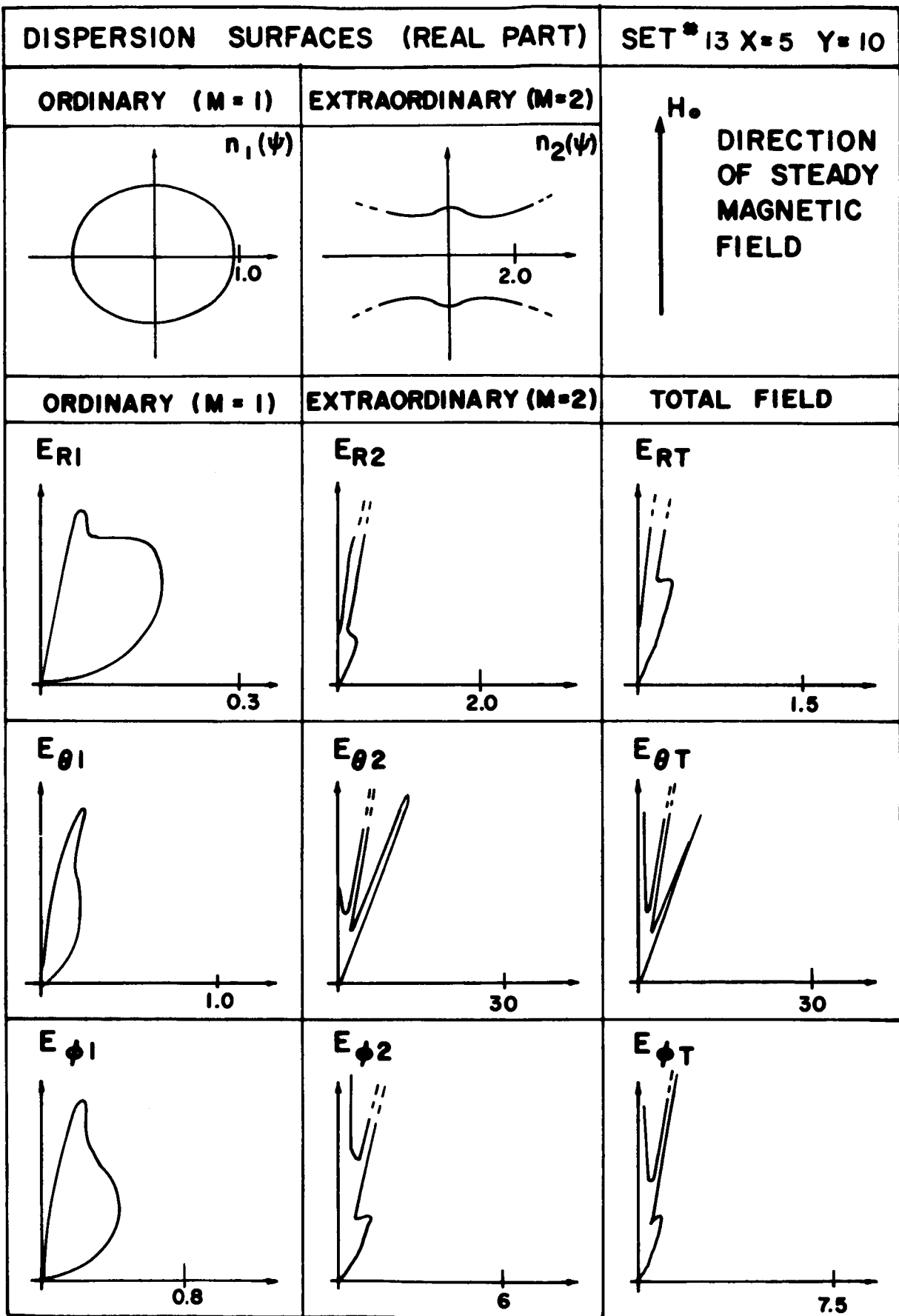


Figure 14.

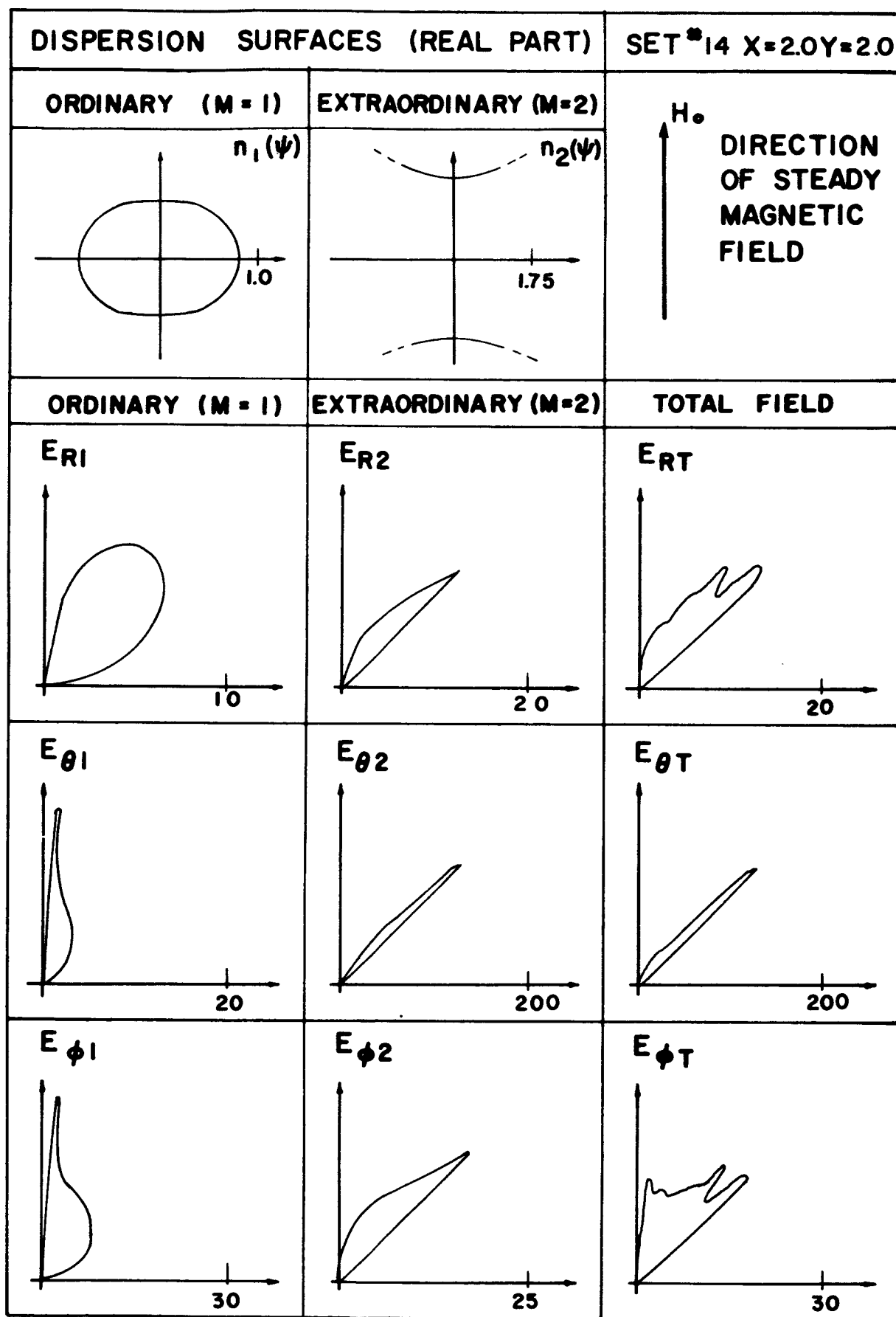


Figure 15.

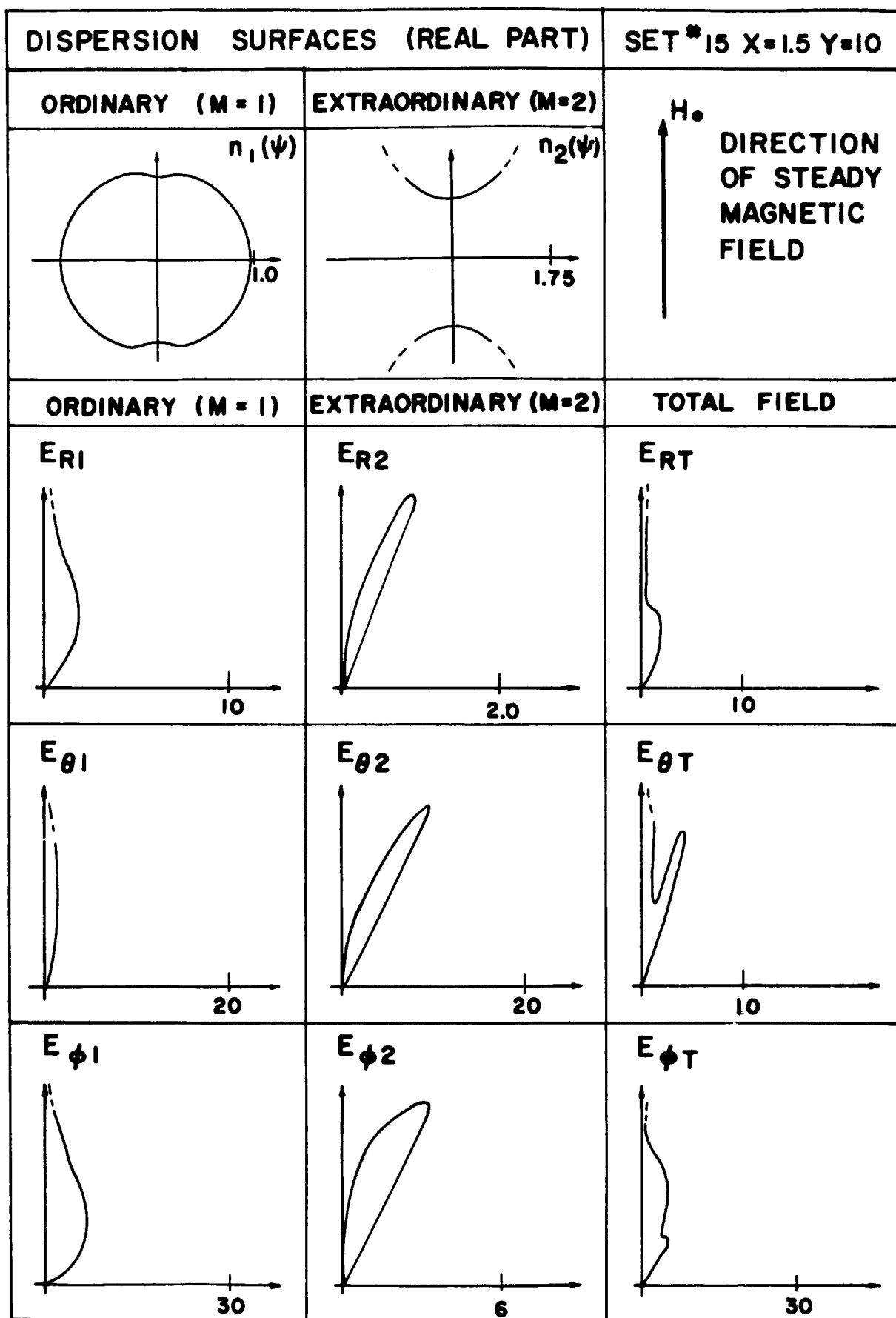


Figure 16.

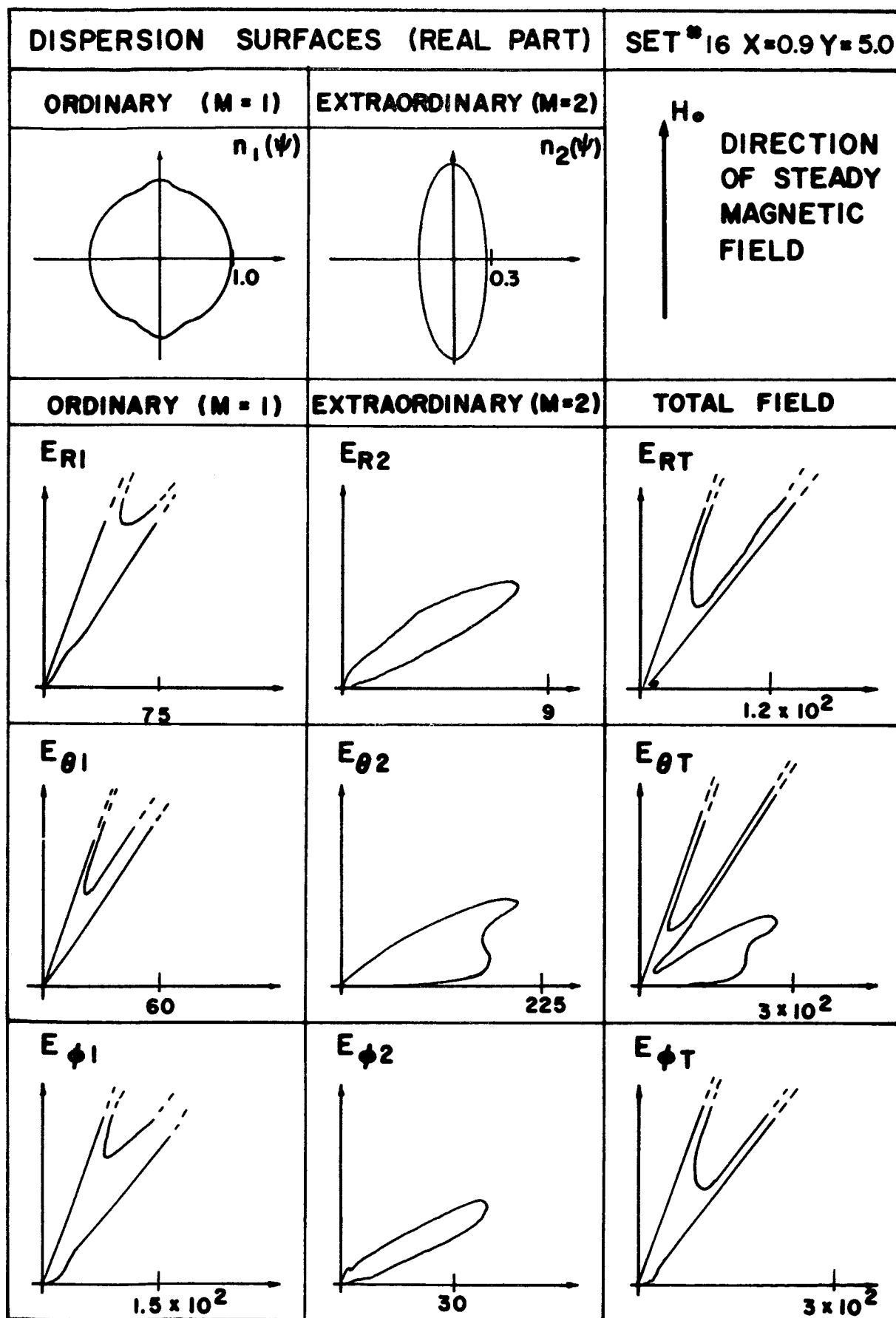


Figure 17.

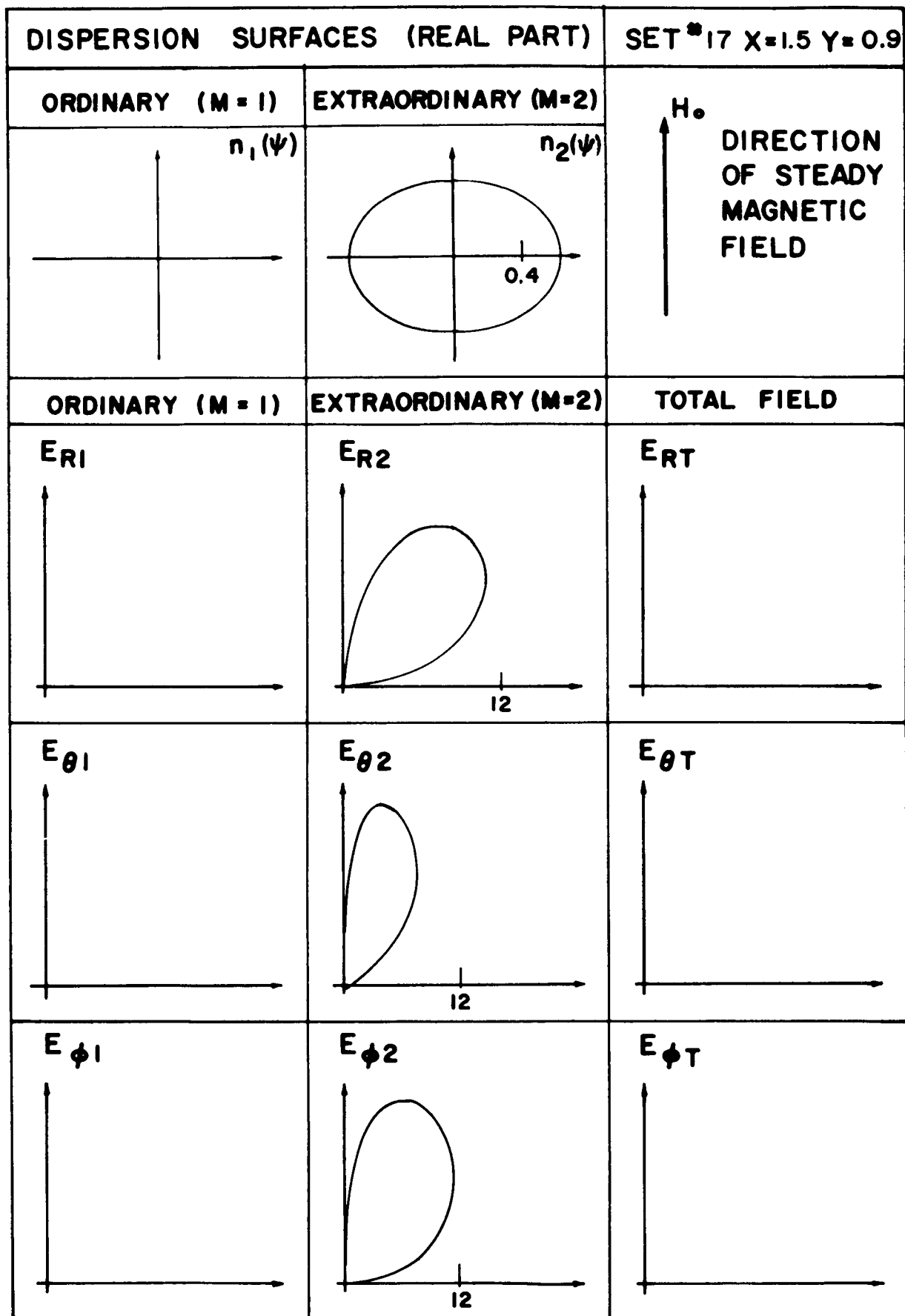


Figure 18.

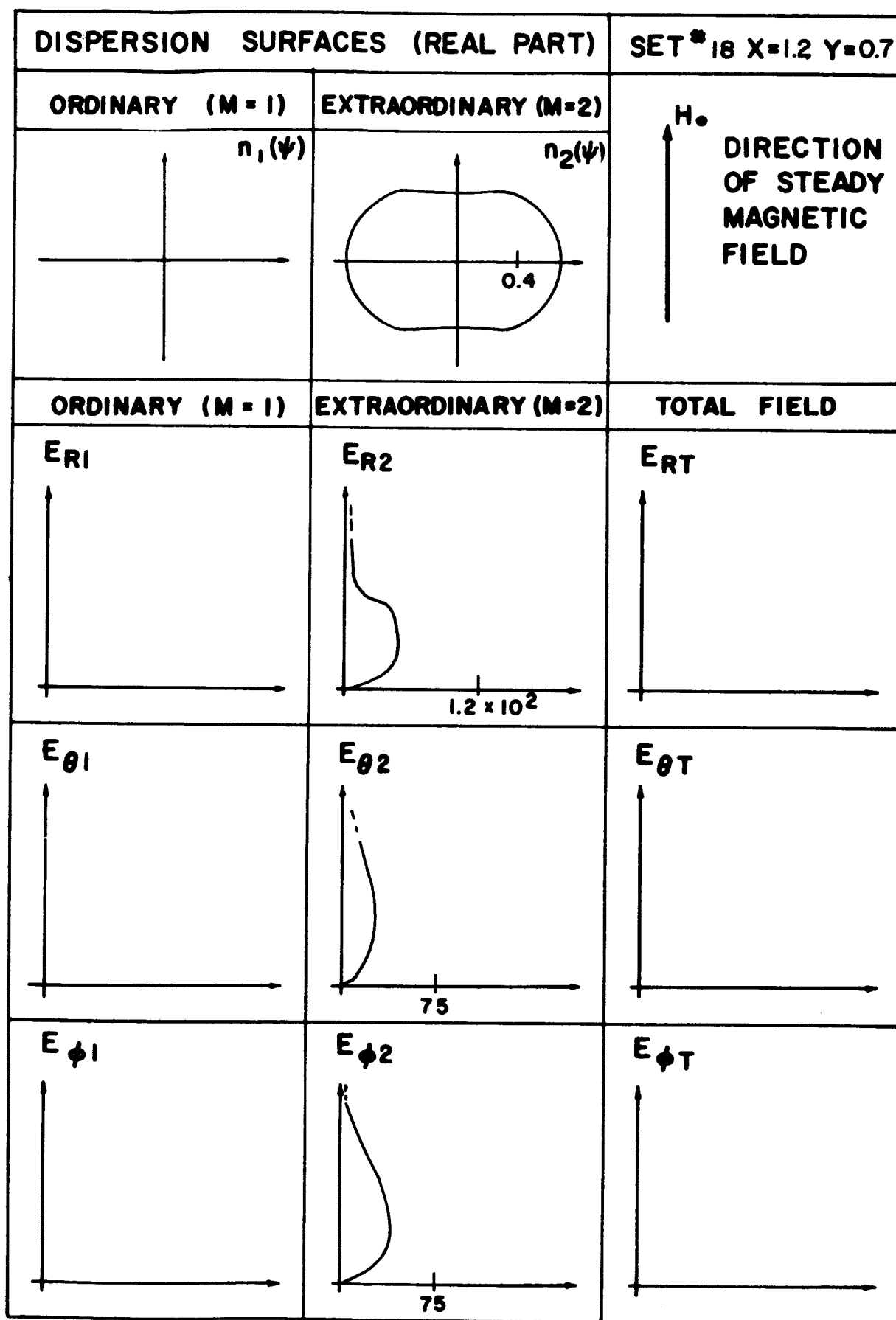


Figure 19.

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